# Search for the Decay $K_S^0 \rightarrow \mu^+\mu^-$†

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A search for the decay $K_S^0 \rightarrow \mu^+\mu^-$ has been completed at the Argonne zero-gradient synchrotron. No event has been found. The upper limit for the branching ratio is $\Gamma(K_S^0 \rightarrow \mu^+\mu^-)/\Gamma(K_S^0 \rightarrow \text{all decays}) < 9.7\times10^{-5}$.

## I. INTRODUCTION

THE existence of neutral leptonic currents in the weak interactions has been conjectured by several authors.[1–5] Good *et al.*[3] and de Rafael[4] note that in the current-current theory of weak interactions there is a lack of symmetry between the hadronic and leptonic currents. Both charged and neutral hadronic currents are allowed while only charged leptonic currents are allowed. They base their model of neutral currents on d'Espagnat's theory of the weak interactions in which the two currents are coupled via the intermediate vector boson $W$, which is assumed to be a unitary triplet consisting of one charged member and two uncharged members. Unlike d'Espagnat, however, they couple the $\mu$ leptons and the $e$ leptons to the $W$'s in symmetrical but different ways. Enough symmetry is preserved to account for all the observed indications of $\mu$-$e$ universality. Their theory is particularly attractive since it leads to the following four main predictions: (1) $\mu$ leptons and $e$ leptons are conserved separately, (2) neutral leptonic currents are absent in all processes involving hadrons, (3) the muon-electron mass difference can be attributed to a neutral $W$ self-energy loop, which is allowed for the muon but not for the electron, and (4) there are differences for the weak interactions of $\mu$ leptons and $e$ leptons in leptonic processes not directly involving hadrons.

The coupling of neutral leptonic currents to hadrons is accomplished through some additional $CP$-conserving interaction of the $W$'s, thereby allowing the emission of $CP$-odd neutral leptonic currents. The interference of these $CP$-odd neutral leptonic currents with the usual $CP$-even neutral lepton pairs induced by electromagnetism gives rise to a small $CP$ violation. Two such possible additional interactions of the $W$'s which introduce $CP$ violation into their theory are explored. The first ($\alpha$ mechanism) is an electromagnetic interaction of the $W$'s via an intrinsic magnetic moment of the neutral $W$'s. Such an electromagnetic interaction would cause emission of $CP$-odd neutral leptonic pairs. The second ($\beta$ mechanism) assumes that the $W$'s feel the effects of the $SU(3)$-violating medium-strong interactions, giving rise to a mass difference between the neutral $W$'s. This destroys the perfect cancellation of strangeness-changing neutral currents in their weak Lagrangian. Interference of the resulting strangeness-changing neutral leptonic currents with the hadron currents creates a $CP$ violation.

For both the $\alpha$ and $\beta$ mechanisms they make various predictions which permit the presence of one or the other to be observed experimentally. For the $\beta$ mechanism, various branching ratios are calculated in terms of a parameter $\beta$ defined as $2(M_3-M_2)/(M_3+M_2)$, where $M_2$ and $M_3$ are the masses of the (neutral) $W_2$ and $W_3$ bosons, respectively. The experiment of Camerini *et al.*[6] places an upper limit on the value of $\beta$ which permits an estimate of $1.2\times10^{-6}$ for the branching ratio $R=\Gamma(K_S^0 \rightarrow \mu^+\mu^-)/\Gamma(K_S^0 \rightarrow \text{all decays})$.

Okubo[5] predicts the existence of $K_S^0 \rightarrow \mu^+\mu^-$ decays through a unified model of $CP$-conserving and $CP$-violating interactions. In his model, intermediate vector bosons are assumed to exist with strong triple interactions between themselves. The weak-interaction Hamiltonian $H_W$ is assumed to be linear in the $W$ field $W_\mu(x)$ and to have a $CP$ parity of $-1$. $H_W$ violates $CP$ invariance maximally and is written as

$$H_W = ig(j_\mu + l_\mu)W_\mu + \text{h.c.},$$

where $g$ is a weak coupling constant and $j_\mu$ and $l_\mu$ are the hadronic and leptonic currents, respectively.

First-order processes in $g$ give zero-matrix elements, second-order processes give the normal weak processes, and third-order processes give the $CP$-violating weak processes. Therefore, $g$ is of the order of $10^{-3}$ from the observed ratio of $\Gamma(K_L^0 \rightarrow \pi^+ + \pi^-)/\Gamma(K_S^0 \rightarrow \pi^+ + \pi^-)$. Decays of the type $K_S^0 \rightarrow \mu^+ + \mu^-$ or $e^+ + e^-$ are expected to occur to order $g^3$, thereby leading to a prediction of $\Gamma(K_S^0 \rightarrow \mu^+ + \mu^-)/\Gamma(K_S^0 \rightarrow \pi^+ + \pi^-) \sim g^2 \sim 10^{-6}$.

Another interesting theory which does not invoke neutral leptonic currents is that of Kitazoe.[7] Kitazoe proposes a quadratic strong interaction between the intermediate vector boson $W$ and the muon. By invoking lepton-baryon symmetry the same quadratic interaction between the intermediate vector boson and the strange particles is obtained. Kitazoe assumes that this interaction is responsible for the breakdown of $SU(3)$

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[1] F. C. Michel, Phys. Rev. **138**, B408 (1965).
[2] T. T. Wu, Phys. Rev. **147**, 1033 (1966).
[3] M. L. Good, L. Michel, and E. de Rafael, Phys. Rev. **151**, 1194 (1966).
[4] E. de Rafael, Phys. Rev. **157**, 1486 (1967).
[5] S. Okubo, Nuovo Cimento **54A**, 491 (1968).
[6] U. Camerini, D. Cline, G. Gidal, G. Kalmus, and A. Kernan, Nuovo Cimento **37**, 1795 (1965).
[7] T. Kitazoe, Prog. Theoret. Phys. (Kyoto) **35**, 288 (1966).

TABLE I. Some experiments seeking neutral leptonic currents.

| Experiment | Decay mode | Result |
|---|---|---|
| Bott-Bodenhausen *et al.*[a] | $K_L^0 \to \mu^+\mu^-$ | $\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \text{all}) < 5.2\times10^{-6}$ |
| | $K_L^0 \to e^+e^-$ | $\Gamma(K_L^0 \to e^+e^-)/\Gamma(K_L^0 \to \text{all}) < 2.5\times10^{-5}$ |
| Abashian *et al.*[b] | $K_L^0 \to \mu^+\mu^-$ | $\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \text{all}) < 5\times10^{-5}$ |
| | $K_L^0 \to e^+e^-$ | $\Gamma(K_L^0 \to e^+e^-)/\Gamma(K_L^0 \to \text{all}) < 5\times10^{-5}$ |
| Bott-Bodenhausen *et al.*[c] | $K_L^0 \to \mu^+\mu^-$ | $\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \text{all}) < 1.6\times10^{-6}$ |
| | $K_L^0 \to e^+e^-$ | $\Gamma(K_L^0 \to e^+e^-)/\Gamma(K_L^0 \to \text{all}) < 1.8\times10^{-5}$ |
| | $K_S^0 \to \mu^+\mu^-$ | $\Gamma(K_S^0 \to \mu^+\mu^-)/\Gamma(K_S^0 \to \text{all}) < 7.3\times10^{-5}$ |
| Fitch *et al.*[d] | $K_L^0 \to \mu^+\mu^-$ | $\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \text{all charged}) \leq 3.5\times10^{-5}$ |
| | $K_L^0 \to \mu^\pm e^\mp$ | $\Gamma(K_L^0 \to \mu^\pm e^\mp)/\Gamma(K_L^0 \to \text{all charged}) \leq 8\times10^{-6}$ |
| This experiment | $K_S^0 \to \mu^+\mu^-$ | $\Gamma(K_S^0 \to \mu^+\mu^-)/\Gamma(K_S^0 \to \text{all}) < 9.7\times10^{-5}$ |

[a] Reference 11.
[b] Reference 10.
[c] Reference 9.
[d] Reference 12.

symmetries among the hadrons. His theory offers explanations both for the muon-electron mass difference and for the large mass of the intermediate vector boson. He predicts the value of $R$ to be approximately $2\times10^{-7}$ and stresses that the $K_S^0 \to \mu^+\mu^-$ decay mode provides a particularly good test of the $\mu$-$W$ interactions. This particular decay mode is forbidden to second order in the electromagnetic interaction and can proceed only in the fourth order with a branching ratio $R$ of approximately $10^{-9}$.

It is also relevant to mention here a recent calculation by Sehgal[8] which uses a recent experimental value for the branching ratio $\Gamma(K_L^0 \to 2\gamma)/\Gamma(K_L^0 \to \text{all decays})$ to compute a value for the branching ratio $\Gamma(K_L^0 \to \mu^+\mu^-)/\Gamma(K_L^0 \to \text{all decays})$ due to electromagnetically induced neutral leptonic currents; a value of $(1.3\pm0.9)\times10^{-8}$ is predicted for this branching ratio.[9]

Among the sensitive tests for the presence of neutral currents are the rates for the following modes of the neutral kaon:

$$K_S^0 \to \mu^+\mu^-, \tag{1}$$

$$K_S^0 \to e^+e^-, \tag{2}$$

$$K_L^0 \to \mu^+\mu^-, \tag{3}$$

$$K_L^0 \to e^+e^-, \tag{4}$$

$$K_L^0 \to \mu^\pm e^\mp. \tag{5}$$

Various experimental measurements of these decays have already been carried out[9–12]; these measurements are summarized in Table I. The purpose of this paper is to report an experiment which gives another measurement of the lower limit for the decay mode (1).

## II. EXPERIMENTAL DETAILS

### A. Beam

The $K_S^0$ mesons were produced by a $(2.9\pm0.5)$-GeV/$c$ $\pi^-$ beam incident on a $CH_2$ target. The beam line is shown in Fig. 1. The beam emerged from the 7° beam port of the ZGS and was focused onto our target by the two quadrupole magnets normally employed in the first stage of the 7° charged beam line used by the MURA 30-in. bubble chamber. The only momentum analysis provided was that by the octant of the ZGS ring magnet in which the internal machine target was located. Because of the rudimentary beam-transport system, the negative beam with the large momentum spread given above was obtained. The momentum resolution obtained was a result of the angular dependence of the pion-production cross section combined with the bending of the particles in the octant magnet. The resulting beam at the $CH_2$ target was rather large and was defined by 4-in.×4-in. scintillation counters. A crude range measurement indicated that about 20% of the beam consisted of muons. Typically, the number of particles (pions and muons) incident on our $CH_2$ target during the 300 msec beam spill varied between $1.0\times10^5$ and $1.8\times10^5$.

### B. Technique

The experimental setup is shown in Fig. 2. The detection apparatus consisted of aluminum foil spark chambers placed in a magnetic field of 10 kG for momentum measurement of the decay products of the $K_S^0$ mesons, followed by 664 g/cm² of steel absorber and 100 g/cm² of aluminum plate range chambers for range

[8] L. M. Sehgal, Nuovo Cimento **45A**, 785 (1966).
[9] M. Bott-Bodenhausen, X. de Bouard, D. G. Cassel, D. Dekkers, R. Felst, R. Mermod, I. Savin, P. Scharff, M. Vivargent, T. R. Willitts, and K. Winter, Phys. Letters **24B**, 194 (1967).
[10] A. Abashian, R. J. Abrams, D. Carpenter, R. E. Mischke, B. M. K. Nefkens, J. H. Smith, R. C. Thatcher, L. J. Verhey, and A. Wattenberg, in *Proceedings of the Thirteenth International Conference on High-Energy Physics, Berkeley, 1966* (University of California Press, Berkeley, 1967).
[11] M. Bott-Bodenhausen, X. de Bouard, D. G. Cassel, D. Dekkers, R. Felst, R. Mermod, I. Savin, P. Scharff, M. Vivargent, T. R. Willitts, and K. Winter, Phys. Letters **23**, 277 (1966).
[12] V. L. Fitch, R. F. Roth, J. Russ, and W. Vernon, Phys. Rev. **164**, 1711 (1967).

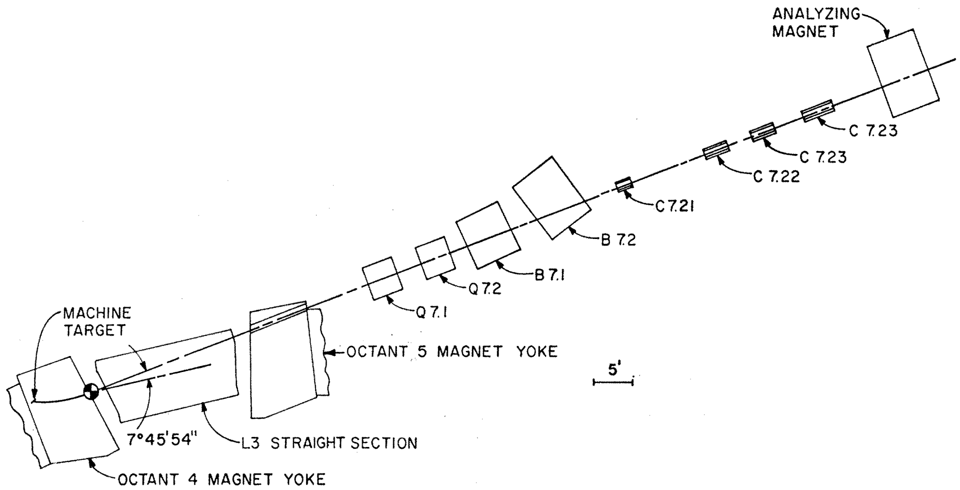


FIG. 1. Beam-transport system. The symbols $Q$, $B$, and $C$ denote quadropole magnets, bending magnets, and collimators, respectively.

measurement. Periodically during the run, the steel block was lifted out and $K_S{}^0 \to \pi^+\pi^-$ data were taken for normalization purposes. To eliminate biases associated with the magnetic field, the direction of the magnetic field was reversed daily during the run.

The triggering mode is summarized in Fig. 2 and functioned as follows. A beam pion produces a pulse in the beam counters $R_1$ and $R_2$. If the beam pion interacts in the target to produce only neutral particles going in the forward direction there will be no pulse in the anticoincidence counter $\beta$, which is just downstream from the target. Thus, the production of only neutral particles is signaled by $R_1R_2\bar{\beta}$. This requirement emphasized the reactions $\pi^-+p \to K^0+\Lambda^0$ and $\pi^-+p \to K^0+\Sigma^0$.

Charged particles resulting from a neutral particle decaying in the decay region downstream from the $CH_2$ target will give pulses in $\alpha$, $M_4$, $M_5$, $\Omega_1$, and $\Omega_4$ in various combinations. If a particle penetrates the steel absorber, a pulse will appear in one of the $P$ counters. The first of two triggering modes used is denoted by $K_A$ and requires the coincidence

$$R_1R_2\alpha(M_4 \text{ or } M_5 \text{ or both})\Omega_1\Omega_4P_{2-6}\bar{\beta}\,,$$

where $P_{2-6}$ gives a signal only if at least two of the six $P$ counters produce pulses. The $K_A$ mode is particularly sensitive to events where the $K_S{}^0$ meson is produced at an angle to the incident pion beam direction. For this case the $K_S{}^0$ decays off of the beam centerline and it is possible for the two charged particles to pass through

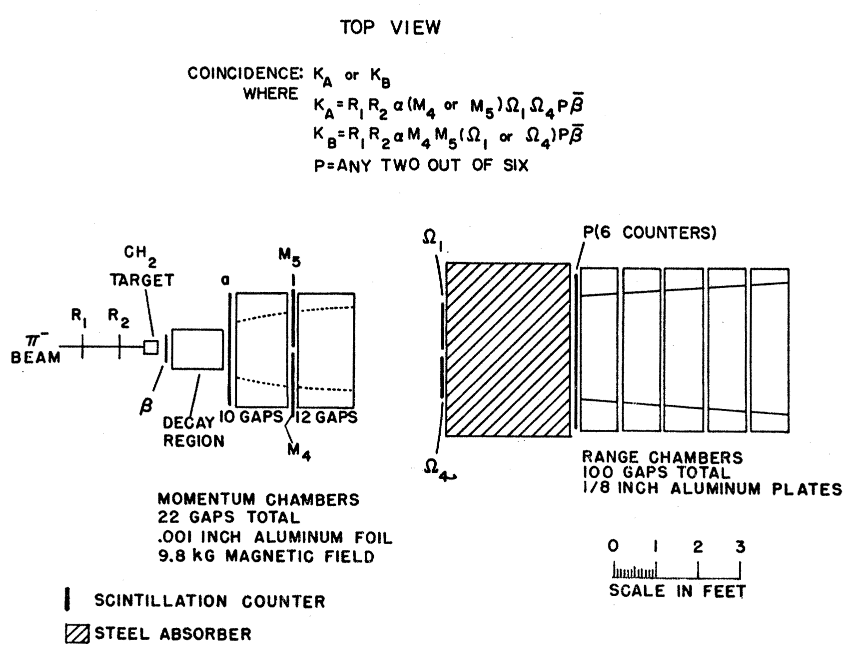


FIG. 2. Schematic of the apparatus and triggering mode used.

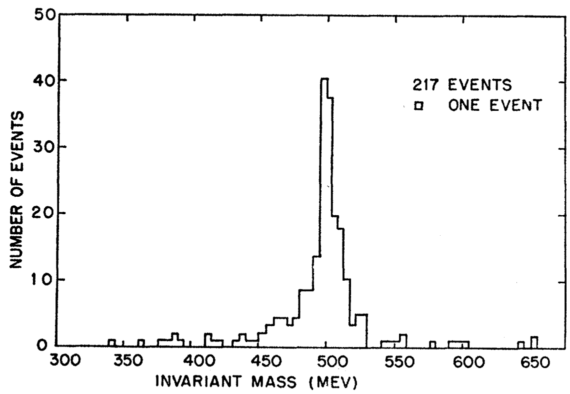


FIG. 3. Invariant-mass histogram for some of the calibration data kinematically fitted assuming the decay $K_S{}^0 \rightarrow \pi^+\pi^-$.

the same "$M$" counter. A second triggering mode $K_B$, which requires the coincidence

$$R_1R_2\alpha M_4M_5(\Omega_1 \text{ or } \Omega_4 \text{ or both})P_{2-6}\bar{\beta}$$

was also used and accounted for approximately 20% of all triggers. The $K_B$ mode is particularly sensitive to events where the $K_S{}^0$ meson is produced almost parallel to the pion beam direction; in this case one of the decay products goes through $M_4$ and the other through $M_5$. The requirement of a single $\Omega$ pulse (either $\Omega_1$ or $\Omega_4$ or both were required) for the $K_B$ mode was dictated by the fact that, oftentimes, the two charged particles from $K_S{}^0$ decay crossed over close to the location of the $\Omega$ counters; this phenomenon resulted from the fact that the magnet aperture and the value of the magnetic field used resulted in particular sensitivity of the apparatus for emission of the decay particles at 90° relative to the $K_S{}^0$ direction in the c.m. system of the $K_S{}^0$. The spark chambers were fired whenever either $K_A$ or $K_B$ was satisfied. The triggering rate with the absorber in place averaged about one in 60 machine pulses. With the absorber out the triggering rate was about one per pulse, of which about 7% were $K_S{}^0 \rightarrow \pi^+\pi^-$ decays.

### C. Apparatus

The counters used were standard scintillation counters made of $\frac{1}{8}$ and $\frac{3}{8}$ in. Pilot $B$ scintillator material viewed by RCA 6655 and 6810 photomultiplier tubes.

The momentum-measuring spark chambers consisted of 21 gaps with $\frac{1}{4}$-in. gap spacing distributed uniformly over a distance of 25 in. The plates of the chamber were made of 12-in.×30-in. brass frames on which 1 mil aluminum foils had been stretched. The chambers were filled with commercial grade neon and were operated at a pulsed voltage of 10 kV. Clearing fields of 15 V were used.

The range spark chambers consisted of five chambers, each of which contained 20 gaps. The plates of the spark chambers were 36-in.×48-in.×$\frac{1}{8}$-in. aluminum sheets and were separated by a distance of $\frac{5}{16}$ in. The operation was the same as for the momentum chambers.

The electronics used consisted of Illinois-designed solid-state modules, very similar to EG&G units.

The magnet used had a pole piece 30-in. deep by 45-in. wide and a gap height of 14 in. The top pole piece consisted of 23 iron plates, $\frac{7}{8}$-in. thick separated by $\frac{3}{8}$ in. Mirrors were placed over each gap in the pole piece, thereby allowing direct viewing of the spark-chamber gaps directly below. Ninety-degree stereo was obtained by placing mirrors in the magnet gap at the side of the spark chambers and viewing through the magnet slots.

## III. DATA ANALYSIS

Ninety-degree stereoscopic pictures were taken of both the momentum-measuring spark chambers and the range-measurement spark chambers. The scanning of the film was done entirely by physicists. Candidates for the decay $K_S{}^0 \rightarrow \mu^+\mu^-$ were selected as follows. The magnet–spark-chamber film was scanned for events in which any two tracks met the following two criteria: (1) the two tracks appeared to originate somewhere within the decay region; (2) the two tracks also appeared to converge in the top view as they travelled toward the rear of the magnet spark chamber. This last criterion was based on the previously mentioned ability of the apparatus to select such events preferentially. If the magnet picture showed more than two tracks, the event was still called a "$\mu\mu$ candidate" if any pair of tracks met the above criteria. The additional tracks resulted usually from rf structure or bunching in the beam and were not related to the event.

The range chambers were scanned independently for "muons," which had to meet the following criteria: (1) one "muon" track had to traverse all five range chambers; (2) the second "muon" track had to pass through at least one range chamber. Even though a track satisfied the above criteria it was called a pion and rejected if (1) the track scattered more than 30° in the range chambers, or (2) the track had an interaction.

After both magnet and range views had been scanned the scanning lists were compared. If an event number occurred on both lists the event was recorded as a "$\mu\mu$ candidate," the magnet view was measured on a Hydel measuring machine, and the event was reconstructed on an IBM 7094 computer. The average rms error in the reconstructed real space spark positions was 0.013 in. A 1-GeV/$c$ particle's momentum could be measured to within 3%. When the two tracks were extrapolated upstream through the fringe field of the magnet, their separation at the point of closest approach (intersection point) had an average value of 0.117 in. in real space. Events were rejected if the separation of the two tracks at the point of closest approach exceeded 0.5 in. Aside from measuring error, the main sources of error in reconstructing the event were the minor variation of the magnetic field due to power supply fluctuations and the accuracy of the magnetic field plot of about $\frac{1}{2}\%$.

Only one $\mu\mu$ candidate was found, and this was easily discarded for several reasons. Mainly, a careful extrapolation of the two tracks backward from the range chambers shows the two tracks to intersect at a point 1 in. upstream from the steel absorber. This is consistent with the vertex being *in* the steel absorber since the reconstructed vertex is only known to about $\pm 4$ in. owing to scattering of the tracks in the steel. Clearly these two tracks could not have come from the decay of a neutral particle inside our decay region. By correlating the two tracks in the magnet picture with the vertex of the extrapolated range chamber tracks, we know that the particle hitting the steel absorber had a negative charge and a momentum of about 1.83 GeV/$c$. (The other track in the magnet picture had a positive charge and a momentum of 0.42 GeV/$c$ and was swept off to the side into the magnet yoke.) The assumption that both tracks were muons gave a reconstructed mass of (408±10) MeV. The assumption that the negative track was an antiproton and the positive track was a pion gave a reconstructed mass of 1130±10 MeV, leading us to believe that the neutral particle whose decay we observed was an antihyperon $\bar{\Lambda}^0$. This assumption would also explain how our apparatus obtained the two pulses from the six "$P$" counters necessary to trigger. It is quite plausible that the antiproton striking the steel annihilated into pions, two of which had sufficient energy to penetrate the remainder of the steel absorber. Consequently, we found no events which possessed all the necessary characteristics of a $K_S{}^0 \to \mu^+\mu^-$ decay.

To calculate the branching ratio, it was necessary to analyze in detail the $K_S{}^0 \to \pi^+\pi^-$ data taken without the steel absorber. The magnet–spark-chamber pictures for the $\pi^+\pi^-$ data were scanned for any two tracks which satisfied the same two criteria as required for the $\mu^+\mu^-$ data. Events meeting the criteria were then measured and reconstructed on the computer to obtain the invariant mass. The range chamber film was not scanned for the $\pi^+\pi^-$ data, since background events fulfilling the scanning criteria (mostly $\Lambda^0 \to p\pi^-$ and three-body kaon decays) were easily rejected on the basis of their reconstructed invariant mass. An invariant-mass histogram for some of the $\pi^+\pi^-$ data taken using a 6-in. $CH_2$ target is shown in Fig. 3. Only events with 480 MeV$<M_{\pi\pi}<$520 MeV were considered to be possible $K_S{}^0$ mesons. A histogram of the decay position along the beam direction for those events satisfying the mass criterion is shown in Fig. 4. Our decay region extended from $Z=-31$ in. to $Z=-19$ in. To allow for errors in tracing the particle trajectories through the magnet's fringe field and to allow for errors in measuring the spark positions off of the film, we accepted events with a $Z$ decay coordinate between $-32.5$ and $-18.8$ in.

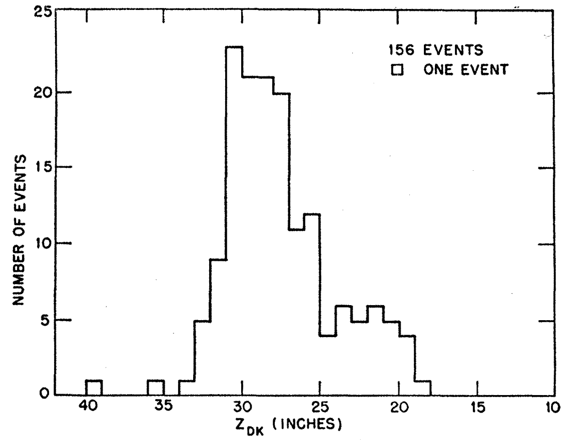


FIG. 4. Decay-position histogram for events of Fig. 2, which satisfy the mass criterion discussed in the text.

Only events which satisfied the mass criterion and which had a decay vertex inside the decay region were considered to be *bona fide* $K_S{}^0$ mesons.

Of the 149 events having 480 MeV$\leq M_{\pi\pi}\leq$520 MeV, four were also kinematically consistent with the decay $\Lambda^0 \to p\pi^-$. Of the 49 events having a two-pion invariant mass outside the limits of the mass cutoff, 16 fitted the $\Lambda^0 \to p\pi^-$ interpretation. This gives a background of approximately one $\Lambda^0$ per 20 MeV interval on the $M_{\pi\pi}$ histogram. Thus, two of the four events consistent with $\Lambda^0 \to p\pi^-$ in the interval 480 MeV$\leq M_{\pi\pi}\leq$520 MeV are probably $\Lambda^0$ decays. Therefore, Fig. 3 shows only 147 *bona fide* $K_S{}^0$ mesons.

As a further check that our events were indeed $K_S{}^0$ mesons, we made a rough measurement of their lifetime using the following method. First, we plotted the energy spectra for $K_S{}^0$ mesons decaying inside our fiducial region for the 3- and 6-in. $CH_2$ targets [Figs. 5(a) and 5(b)]. The average kaon energy $\bar{E}_K$ was 2.35 GeV for the 3-in. data and 2.72 GeV for the 6-in. data. The average kaon energy is lower for the 3-in. data than for the 6-in. data since a larger fraction of low energy $K^0$'s survive passage through the thinner target without being rejected by the anticoincidence counter. Defining the origin of coordinates at the upstream end of a target, we then computed the average point of production $X_0$ for $K_S{}^0$ mesons produced in the target and decaying inside our fiducial volume, taking into account both the attenuation of the pion beam as it traversed the target and the decay of $K_S{}^0$ mesons upstream of the $\beta$ anticounter. For the 3-in. data, $X_0=1.7$ in. and, for the 6-in. data, $X_0=3.4$ in. For each event with energy $E_K$ and decay point $X$ (measured along the beam direction), we define a proper time, $t=(X-X_0)/\beta\gamma c$, where $\gamma=E_k/M_k=(1-\beta^2)^{-1/2}$. The detection efficiency of our apparatus was computed separately for each proper time bin using the Monte Carlo program discussed in the Appendix. The data in each bin were then corrected for the efficiency for that bin. Both the 3- and 6-in.

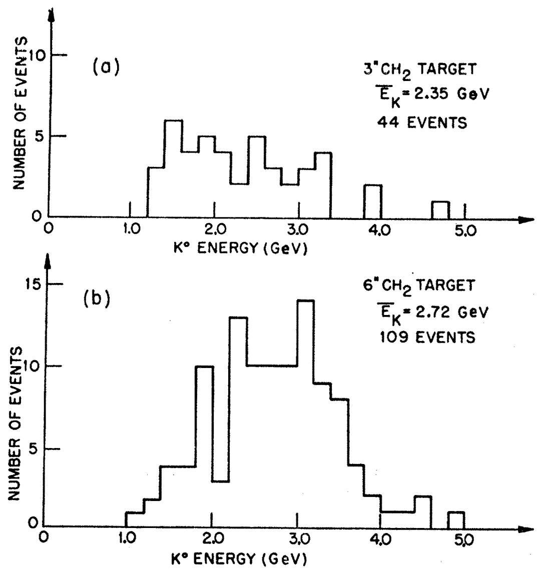


FIG. 5. Kaon-energy histograms for events satisfying the invariant-mass and decay-position criteria.

data, with the efficiency folded in, were used to make the semilogarithmic plot of the number of events as a function of proper time which is shown in Fig. 6. The least-squares fit to the data of Fig. 6 gives a value of $(0.9\pm0.2)\times10^{-10}$ sec for the lifetime of the $K_S{}^0$ meson, in good agreement with the accepted value.

The number of *bona fide* $K_S{}^0$ mesons decaying into $\pi^+\pi^-$ was normalized to the number of pions incident on the $CH_2$ target as recorded by the beam counter telescope $B=R_1R_2\alpha\beta$. Since the $\pi^+\pi^-$ decay mode of the $K_S{}^0$ occurs only 68.4% of the time, the number of $K_S{}^0$ mesons produced was scaled up by a factor of 1.46.

The extrapolation from $K_S{}^0\to\pi^+\pi^-$ rates to $K_S{}^0\to\mu^+\mu^-$ rates involves another correction, namely, that the two muons be emitted with enough energy to penetrate the absorber. We found the number of $K_S{}^0$ mesons whose $\mu^+\mu^-$ decay could be detected in our apparatus was only 20% of the total number of $K_S{}^0$ mesons whose $\pi^+\pi^-$ decays were observable with the absorber removed. The figure of 20% was computed in the following way. Using the range-momentum curves of Ref. 13, we computed the minimum momentum a muon needed to penetrate 664 g/cm$^2$ of steel plus 18 g/cm$^2$ of aluminum and obtained a value of 1.2 GeV/$c$. We then counted the number of $K_S{}^0\to\pi^+\pi^-$ events in our calibration sample for which *both* pions had momenta in excess of 1.2 GeV/$c$; there were 31 events meeting this condition. Thus, neglecting the mass difference between muons and pions, we found only 20% (=31/147) of the hypothetical $K_S{}^0\to\mu^+\mu^-$ decays could be observed with our apparatus.

Including all of the factors discussed in the preceding paragraphs we obtain a yield of $(2.0\pm0.2)\times10^{-7}$ $K_S{}^0$ mesons per count in the monitor telescope $B=R_1R_2\alpha\beta$ using the 6-in. $CH_2$ target; the error given is statistical only. This experimentally determined value agrees with the calculated value of $(1.8\pm0.5)\times10^{-7}$ $K_S{}^0$ mesons per monitor count which was computed using the measured production cross sections for $\pi^-+p\to K^0+\Lambda^0$ and $\pi^-+p\to K^0+\Sigma^0$ and the detection efficiency of our apparatus obtained from the Monte Carlo program. The error in the calculated yield comes mainly from the quoted errors in the production cross sections[14] and from approximations in the Monte Carlo program. Normalizing all the data to those taken with the 6-in. $CH_2$ target, we obtained an effective total of $5.1\times10^{10}$ "$B$" monitor counts for all of our runs made with the steel absorber. Using the experimentally determined yield given above, this gives a total of $1.03\times10^4$ $K_S{}^0$ mesons whose $K_S{}^0\to\mu^+\mu^-$ decay mode we could have seen. If one visible decay had been observed, the branching ratio $R=\Gamma(K_S{}^0\to\mu^+\mu^-)/\Gamma(K_S{}^0\to \text{all decays})$ would have been $9.7\times10^{-5}$. No events were observed. An upper limit of $7.3\times10^{-5}$ for $R$ has recently been reported by Bott-Bodenhausen *et al.*[9] Combining our result with that of Ref. 9, the present value of the branching ratio is $R\leq4.2\times10^{-5}$.

## IV. DISCUSSION

The results of this experiment are clearly inadequate for testing the theoretical estimates for the rate of

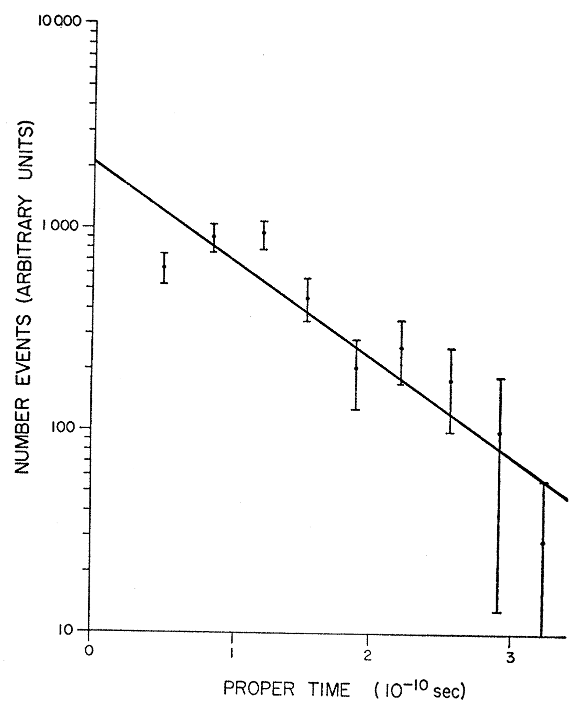


FIG. 6. Number of $K_S{}^0\to\pi^+\pi^-$ decays, corrected for detection efficiency, versus the proper time. The line is the least-squares fit to the data points.

[13] W. P. Trower, University of California Radiation Laboratory Report No. UCRL-2426 Berkeley 1966, Vol. IV (unpublished).

[14] R. W. Hanft, thesis, University of Illinois, 1967 (unpublished).

$K_S{}^0 \to \mu^+\mu^-$ by about a factor of 100. Improvements in the experiment in terms of increased incident beam intensity, improved detection efficiency and solid angle, and improved momentum resolution are easily feasible. Experiments of the order of $R=10^{-7}$ are not unreasonable and will be able to test for the existence of weak neutral currents.

## ACKNOWLEDGMENTS

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## APPENDIX

We used a Monte Carlo program to compute the relative detection efficiency of our apparatus. $K_S{}^0$ mesons were assumed to be produced in our $CH_2$ target with an angular distribution peaked strongly forward and an energy spectrum estimated using the pion beam momentum spectrum as well as the production kinematics for the main production reaction $\pi^- + p \to K^0 + \Lambda^0$. Because of the large momentum spread of the incident $\pi^-$ beam, it was very difficult to estimate the kaon-energy spectrum. Consequently, we decided on the following iterative procedure. Besides computing the detection efficiency, the Monte Carlo program also compiled the energy spectrum of those $K_S{}^0$ mesons whose decays would have been successfully detected in our apparatus. This "output" spectrum was then compared to the measured energy spectrum obtained from our $K_S{}^0 \to \pi^+\pi^-$ data and corrections made to the input spectrum. Iteration was continued in this manner until the "output" energy spectrum produced by the Monte Carlo program agreed with the measured spectrum.

The kaon's energy was selected using a random-number distribution weighted according to the input-energy spectrum. As each event was generated its energy was recorded in a table to produce an energy spectrum for all events generated. This provided a check to insure that the program was really generating events according to the input energy spectrum which we had fed into it. Once its energy had been chosen the kaon travelled downstream until it reached its decay point. The decay point was determined from another random-number distribution weighted exponentially according to the $K_S{}^0$ lifetime and the energy of the kaon. For normalization purposes the decay point of each event generated was recorded in another table consisting of 1-in. bins along the beam direction. Next, the angles of one of the decay pions in the c.m. system of the kaon were chosen randomly, and relativistic kinematics was used to transform the two pion momenta into the laboratory coordinate system. A subroutine then tracked each pion through the actual magnetic field, mapped before the start of the experiment. As the pions progressed through the magnet, the program checked to see if they hit the combinations of scintillation counters necessary to trigger the apparatus, and if their tracks were in the region of the magnet where they could be seen in the spark chambers. Events not meeting the necessary criteria were recorded as "misses" and the program returned to generate the next event. Events meeting all criteria were recorded as "hits." For each hit the kaon energy was recorded in the spectrum of successful events and the decay point was recorded in a table consisting of 1-in. bins along the beam direction.

After the desired number of events had been generated the program computed the relative efficiency for each 1-in. bin by dividing the number of hits for that bin by the number of tries for that bin. The resulting efficiency obtained was a smoothly varying function along the beam direction and was not particularly sensitive to the exact shape of the input-kaon-energy spectrum. For the final run of the program 67 754 $K_S{}^0 \to \pi^+\pi^-$ decays were generated, of which a total of 2950 fulfilled all the conditions necessary for detection in our apparatus.